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SURVEY ON MULTIPHASE INDUCTION MOTOR SPEED CONTROL

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Abstract

Multiphase induction motor drives have a few benefits over traditional three-stage drives, for example, lower torque pulsation, adaptation to non-critical failure, steadiness, high effectiveness and lower current wave and decreased current per phase without increasing voltage per phase and so forth. This paper outlines the historical advancement of multiphase machines and drive strategies. Multiphase machines are acquiring increasing popularity due to their particular potential benefits over three-phase counterparts, for example, decreased per phase power rating, increased degree of freedom and improved reliability. We will discuss different motor control techniques in this section, including direct torque control (DTC), model predictive control (MPC), and model predictive control (MPC). We will also cover the fault-tolerant technique and the vector-space decomposition (VSD) strategy. We will also mention other existing multiphase converter methods and other multiphase PWM methods. The number of stages for which an approach can be achieved has been assessed for various applications. In multiphase converters, it is crucial that the current is transported evenly between stages. It is favored that the closed-loop dynamic model is linear in a wide range voltage and current, where control signal limits, parameter variation, dead time impacts are all considered. From the survey, considering the different types of multiphase induction motor drives, the DTC has a higher dynamic torque response while the FOC have an improved steady state behavior, it also produces lower harmonic current which improves efficiency.

1 INTRODUCTION

Multi-Phase machine drives are quick expanding as of late, because of their advantages, for example, decrease in stator current per phase, reduction in harmonic current, lower torque pulsation, without the need to raise the phase voltage, increased power, fault tolerant feature, power in a similar casing when contrasted with three phase machine. They are generally utilized in high power applications, like boat drive, electric airplane, and electric vehicles and so forth, as revealed in [1]. Modeling of multi-phase induction motor control is portrayed in [2]. Multi-phase motor operates with multi-phase voltage source inverter (VSI). An inverter technique utilizes two switches arranged in series as one set of inverter. However, the number of inverter poles relies upon number of phases of the motor. The space vector pulse width modulation (SVPWM), sinusoidal pulse width modulation (SPWM) method, harmonic injection method and offset injection strategy of three phase inverters are broadly examined in [3].

The SPWM and the SVPWM methods in multiphase are clearly discussed in details [4]. Three phase inverters are examined in [3]. The SPWM and the SVPWM methods are examined in detail in [4]. Space vector pulse width modulation (SVPWM) is a more adaptable and simple method of pulse width modulation than the space vector pulse width modulation (SPWM) method. Space vector pulse width modulation (SVPWM) procedures are presented in [2]. In order to achieve an improved output voltage, some space vector pulse width modulation (SVPWM) procedures are deliberated. The space vector SVPWM, the discontinuous SVPWM, multi-dimensional SVPWM and the conventional SVPWM drives are mentioned.

The intricacy engaged with the SVPWM strategy [5] is greater in higher number of phases. It is seen that since there are $2n$ different exchanging arrangements, the output voltage vector of the inverter changes to 2n state. Thus the SVPWM has convoluted controlling procedure to identify its amplitude, voltage space vector and angle information. Subsequently, a straightforward and simple switching procedure is required for multi-phase voltage source inverter which would eliminate intricacy associated with higher number of phases. This work assesses the performance and the behavior of the multi-phase VSI [6, 7] with the improved PWM procedures specifically offset injection strategy, which is regularly utilized for three-phase VSIs which can be applied in or multi-phase. The methodology applied in this work is by surveying different articles and previous works from different database in relation to methods of controlling multiphase induction motors.

Speed control of multiphase induction machines are in principle the same as in the three-phase induction machines. In the early days of multiphase variable-speed induction motor drive development, the focus was on controlling constant-frequency switching [8, 9]. Constant variable frequency control was comprehensively studied in the case of voltage source inverters operating in the conduction mode and current source inverters with quasi square-wave current output [10-16].

2 THE INDUCTION MOTOR

An induction motor (an asynchronous motor) [12] generates a rotating magnetic field in the stator by speeding up the rotor of an induction motor. This induced current in the rotor's AC windings or squirrel cage is caused by the rotor's slightly slower speed than the stator's rotating magnetic field. Slip, a difference in rotational speed, occurs [13]. Because induced coil currents create a second phase during operation, shaded-pole induction motors appear to be two-phase motors with a short-circuit winding that creates a rotating field in the gap [9,5]. Single-phase induction motor types are not the most effective. Although they are not as efficient as multi-phase induction motors, they are widely used in both commercial and domestic settings. They are desirable for their simple design, low cost, and dependability, as well as for their availability in single-phase voltage sources. If single-phase motor drives that may be controlled for speed are required, single-phase frequency converters [16] and small three-phase motors are available. This is the trend to enhance energy efficiency.

Figure 1 Diagram of an Induction motor

Three-phase induction motors are mostly used in the industry. Slip-ring induction motors are the most common type of induction motor. They are driven by AC current transmitted to the active rotor coils via slip rings, which are commonly referred to as slip-ring induction motors. Squirrel-cage induction motors are the second type. The external rotor resistors on slip-ring induction motors [18] provide a high starting torque, smooth acceleration under heavy loads, adjustable speed, and excellent running characteristics.

The doubly fed induction generator, a slip-ring machine, remains the most popular generator type for wind turbines, despite their general popularity and market share having dropped off significantly recently. Squirrel-cage induction motors [11, 19] are simpler and tougher in construction. [20, 21]. They are relatively inexpensive and require little maintenance, and they are used on lathes, drilling machines, pumps, and compressors, among other applications.

AC DRIVE CONTROL

There are several ways to convert AC power into input suitable for controlling AC motor speed and torque [20, 21]. Pulse-width modulation (PWM) and six-step or trapezoidal voltage conversion are two of them [20, 21]. AC motor speed and torque are controlled by converting the voltage input into a six-step or trapezoidal voltage signal [22].

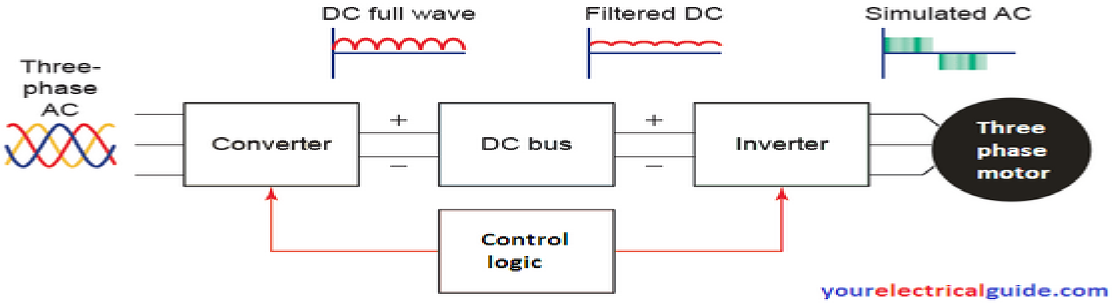

Figure 2 Diagram of a Variable Frequency Drive

Voltage (and current) is rapidly turned on and off, resulting in a varying voltage (and current) average [19, 23]. Duty cycle is the relative duration of the on and off periods, which determines voltage output [19, 23]. The voltage level is controlled by adjusting the on and off periods. The length of the on and off periods, in terms of time, determines voltage. The voltage is expressed as a percentage with a value of 100% being the highest voltage. PWM is unsuitable for inductive loads because it assumes inductance. With inductance, voltage can be stored in the magnetic circuit to maintain a smooth current flow, in spite of the PWM supply.

An AC drive [8] should operate smoothly when switched on and off in response to PWM because the motor must receive short on-off switching pulses that are quick relative to the time it takes the load to react. The PWM waveform must appear smooth to the load. Typically, AC drives [48] operate at a few to ten kHz. To generate AC drives that vary the voltage and frequency of their motor input power, induction motors and synchronous motors are increasingly being coupled with power electronics switching systems to produce variable-torque AC drives [24, 25, 26].

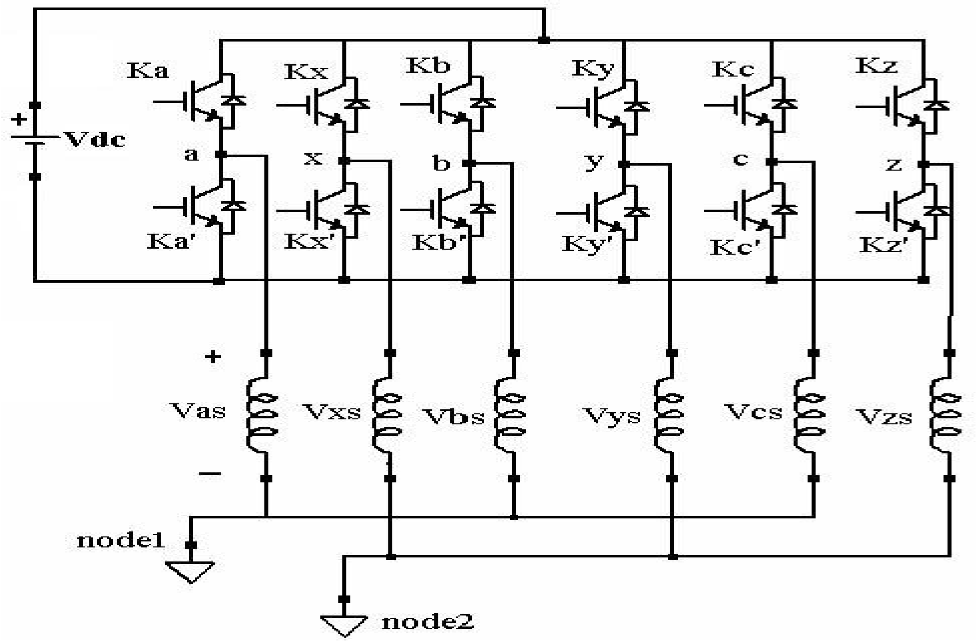

Figure 3 Diagram of Six-phase induction motor drive from a six-phase inverter.

In addition to significant energy savings opportunities in fan, pump, and compressor applications [17], induction motors may also offer important energy savings opportunities [27].

INDUCTION MOTOR CONTROL

Induction motor speed control [16] is a process of causing currents in an induction motor to achieve a change in speed.

Induction motors operate through magnetic field coupling [28, 29] in the stator and rotor. Rotating magnetic is produced by the current in the stator that induces a lagging magnetic field in the rotor. The interaction of the magnetic fields causes the rotor to rotate at an angular speed. This angular speed is usually less than the rotating speed of the stator field. The slip generates torque at the shaft of the motor. Speed control [15] using field-oriented control regulates Id and Iq such that the flux is proportional to Id and the torque is proportional to Iq.

Modeling of multiphase induction machines [21, 30] provides sufficient means for dealing with mathematical representation of an induction machine with an arbitrary number of phases on both stator and rotor using the symbols below

L_S	Stator inductance
L_m	Manuel inductance
L_r	Rotor Inductance
R_S	Stator resistance
R_e	Cabale resisitance
w_0	Rotor Speed
P_x	Pole number
$V_{ds.}\,_{V_{qs.}}$	d-axis and q-axis component of the stator voltage vector $V_{s.}$
$V_{dr.}\,_{V_{qr.}}$	d-axis and q-axis component of the stator voltage vector $V_{r.}$
$i_{ds.}\,_{i_{qs.}}$	d-axis and q-axis component of the stator current vector $i_{s.}$
$i_{dr.}\,_{i_{qr.}}$	d-axis and q-axis component of the rotor current vector $i_{r.}$
j	Moment of inertia of rotor
j_l	Momentg of inertia of load

Machines can also be modeled effectively with windings sinusoidally distributed in order to account for the higher spatial harmonics. Probably, the most comprehensive treatment of the modeling procedure at a general level is available in [20, 21]. Modeling of an n-phase induction machine, with higher spatial harmonics is being detailed in [28] also; specific case of a five-phase induction machine has been investigated in [17]. Phase-variable models are transformed using real complex or real matrix methods of transformation which will give rise to corresponding space vector or real models of the multiphase machine. A slightly different approach to the multiphase machine modeling is discussed in [45, 50].

It is termed 'vectorial modeling' and it represents a kind of generalization of the space vector theory, applicable to all types of AC machines [31]. In principle, it leads to the same control schemes for multi- phase machines [20, 32] as do the transformations of the general theory of electric machines. A summary of the modeling technique based on the general theory of electric machines is provided. An n-phase symmetrical induction machine [33, 34], such that the spatial displacement between any two consecutive stator phases equals α=$2\pi/n$, is considered. Both rotor and stator windings are regarded as n-phase and the windings are distributed sinusoidally, meaning that all higher spatial harmonics of the magneto-motive force can be neglected. The phase number n can either be odd or even. For example, a decoupling transformation matrix [35] of a phase number n; can be given in power invariant form below;

$$\underline{C} = \sqrt{\frac{2}{n}}\;\begin{array}{c} \alpha \\ \beta \\ x_1 \\ y_1 \\ x_2 \\ y_2 \\ \dots \\ x(n-4)\sqrt{2} \\ y(n-4)\sqrt{2} \\ 0_+ \\ 0_- \end{array} \begin{bmatrix} \mathbf{1} & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \dots & \cos 3\alpha & \cos 2\alpha & \cos\alpha \\ \mathbf{0} & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \dots & -\sin 3\alpha & -\sin 2\alpha & -\sin\alpha \\ \mathbf{1} & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \dots & \cos 6\alpha & \cos 4\alpha & \cos 2\alpha \\ \mathbf{0} & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \dots & -\sin 6\alpha & -\sin 4\alpha & -\sin 2\alpha \\ \mathbf{1} & \cos 3\alpha & \cos 6\alpha & \cos 9\alpha & \dots & \cos 9\alpha & \cos 6\alpha & \cos 3\alpha \\ \mathbf{0} & \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \dots & -\sin 9\alpha & -\sin 6\alpha & -\sin 3\alpha \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \mathbf{1} & \cos\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos 3\left(\frac{n-2}{2}\right)\alpha & \dots & \cos 3\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos\left(\frac{n-2}{2}\right)\alpha \\ \mathbf{0} & \sin\left(\frac{n-2}{2}\right)\alpha & \sin 2\left(\frac{n-2}{2}\right)\alpha & \sin 3\left(\frac{n-2}{2}\right)\alpha & \dots & -\sin 3\left(\frac{n-2}{2}\right)\alpha & -\sin 2\left(\frac{n-2}{2}\right)\alpha & -\sin\left(\frac{n-2}{2}\right)\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & \dots & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & \dots & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix}$$

Clarke’s decoupling transformation matrix for a symmetrical n-phase system

A star connected winding of a motor is usually made to have a common neutral irrespective of the number of phases. The original form of the machine model is transformed using decoupling (Clarke's) transformation matrix [3], hereby replaces the previous sets of variables with a new set of variables, where $\alpha=2\pi/n$.

The first two rows of the matrix define variables that will result in fundamental flux and torque production. The last two rows define the two zero-sequence components and the last row of the transformation matrix is omitted for all odd phase numbers *n* [35,36]. Between them, there are *(n-4)/2 (or (n-3)/2 for n= odd*) pair of rows which define *(n - 4)/2 (or (n 2-3)/2 for n odd)* pairs of variables, termed further on x - y components. Considering the equations for pairs of *x* - *y* components, it is clearly seen that they decoupled from all other components and the rotor to stator coupling is eliminated [3, 20]. The winding of the rotor is usually short- circuited hence, neither *x* - *y* nor zero-sequence components may exist, and one may only consider further on *α-β* of the rotor winding equation [37, 38].

It is seen that the rotor to stator coupling takes place only in *α-β* equations [14,39] and these two pairs of equations represents the rotational transformation taking an identical form of a three-phase machine. The machine equations may be arbitrarily transformed into a frame of reference rotating at angular speed *ωa,* and the model of an *n*-phase induction machine having a sinusoidal winding distribution is represented as:

$$V_{ds} = R_{s\,ids} - \omega_{a\psi qs} + P\psi_{ds}$$

$$V_{ds} = R_{s\,iqs} + \omega_{a\psi ds} + P\psi_{qs}$$

$$V_{xIs} = R_{sixIs} + \omega P\psi_{XIs}$$

$$V_{yIs} = R_{siyIs} + P\psi_{yIs}$$

$$V_{x2s} = R_{six2s} + P\psi_{x2s}$$

$$V_{y2s} = R_{si2s} + P\psi_{x2s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$V_{0+s} = R_{sio+s} + P\psi_{0+s}$$

$$V_{0+s} = R_{sio-s} + P\psi_{0-s}$$

$$V_{dr} = 0 = R_{ridr} - (\omega_{a} - \omega)\,\psi_{qr} + P\psi_{dr}$$

$$V_{qr} = 0 = R_{riqr} - (\omega_{a} - \omega)\,\psi_{dr} + P\psi_{qr}$$

$$\psi_{ds} = (L_{IS} + L_{m})i_{ds} + L_{midr}$$

$$\psi_{qs} = (L_{IS} + L_{m})i_{qs} + L_{midr}$$

$$\psi_{Xis} = L_{ISixIs}$$

$$\psi_{yis} = L_{ISiyls}$$

$$\psi_{x2s} = L_{ISix2s}$$

$$\psi_{y2s} = L_{ISiy2s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\psi_{0+s} = L_{ISi0+s}$$

$$\psi_{0-s} = L_{ISi0-s}$$

$$\psi_{dr} = (L_{Ir} + L_{m})i_{dr} + L_{m}\,i_{ds}$$

$$\psi_{qr} = (L_{Ir} + L_{m})i_{qr} + L_{m}\,i_{qs}$$

where $L_m(n/2)\,M$ and *M* = the maximum value stator to rotor mutual inductances

R and L = resistance and inductance,

v, i and ψ = voltage, current and flux linkage

s, r = stator/rotor variables/parameters.

Torque equation is given as

$$T_e = PL_m[I_{dr}I_{qs} - I_{ds}I_{qs}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3)$$

The model equations for d-q components in (1) and (2) and the torque equation (3) are identical for a three-phase induction machine and multiphase induction machines, as well as the three-phase motors. In essence, x-y components refer to certain voltage and current harmonics, which depend on the machine's number of stator phases [40].

BASIC CONTROL PRINCIPLES FOR ELECTRIC MACHINES

Vector control of AC induction motor

In a squirrel-cage motor, a laminated steel rotor embedded with a squirrel-cage configuration of copper or aluminum conductors is used to produce AC induction. Scalar control methods based on DOL control are simple and a long established method. The control of squirrel-cage machines is often achieved using the simplest and most traditional scalar control method. Steady state phasor equations predict motor behaviours in these cases, but are imprecise during transients, becoming less and less precise as a result. With this technique, control is precise at steady state but imprecise during transients, resulting in an increased uncertainty of control. It is possible to regulate voltage using PWM [19].

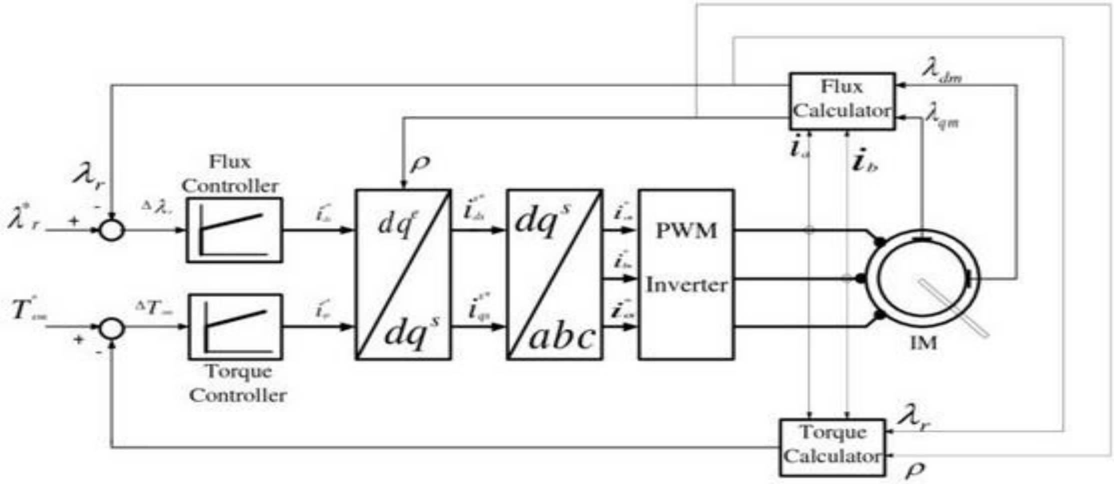

Figure 4 Diagram of a Direct Vector control

An AC machine vector control approach [9, 46] is either field-oriented control or direct torque control (FOC or DTC). In FOC, AC machine currents are controlled to produce a desired flux linkage and torque or force. The DTC approach [47] is based on DFLC. Electrical torque in rotary AC machinery is the cross product of the stator current space vector and the space vector for stator flux linkage. Electrical torque in rotary AC machinery can be expressed as the cross product of the space vector for stator flux linkage and the stator current space vector as follows.

$$T_e = \frac{3}{2}P\Psi_s\, X\, i_s = \frac{3}{2}P\frac{L_m}{L_r}\Psi_r\, X\, i_s$$

The right-hand side of the expression is valid for an induction machine and is used especially in FOC. The equation for torque is the sum of the absolute value of the angle and the sine of the angles [34]. The angle between the two vectors is a vector parallel to the shaft of the machine. The first part of the equation may be expressed as scalar quantity below.

$$T_e = \frac{3}{2}P/\,\Psi_s//i_s/\,\sin\gamma'$$

T_e is the electromechanical torque vector

$Ŧ_e$	is the absolute value of the electrical torque,
p	is the number of pole pairs,
i_s	is the stator current space vector,
ψ_s	is the space vector for stator flux linkage, and
γ'	is the angle between the above two vectors

This expression results in a positive value when the current rotates in the positive direction ahead of the flux linkage ($\gamma > 0$). This would be a motor drive. If ($\gamma < 0$) or the flux linkage is ahead of the current, it would be a generator drive.

The rotor flux linkage consists of the air gap portion, produced by the sum of the stator and rotor current vectors, and the rotor leakage.

$$\Psi_r = (i_s + i_r)L_m + L_{r\sigma} i_r = i_s L_r + L_m i_s$$

Therefore, the rotor current vector is as follows,

$$i_r = \frac{\Psi_r - L_m i_s}{L_r}$$

The stator flux linage is formulated similarly. It consists of the air-gap flux linkage, which is produce y the sum of the stator and rotor current vectors and the stator leakage.

$$\Psi_s = (i_s + i_r)L_m + i_{rs} L_{s\sigma} = L_s i_s + L_s i_s + L_m i_r$$

Inserting this solution for rotor current yields

$$\Psi_s = L_s i_s + L_m \frac{\Psi_r - L_m i_s}{L_r}$$

Inserting in the torque equation gives the desired result.

$$T_e = \frac{3}{2} P \Psi_s \, X \, i_s = \frac{3}{2} P \left(L_s i_s + \frac{L_m}{L_r} (\Psi_r - L_m i_s) \right) X \, i_s = \frac{3}{2} P_{L_r}^{L_m} \, \Psi_r \, X \, i_s$$

Therefore, IM torque can be expressed as the cross product of the rotor flux linkage and the stator current.

Direct Torque Control (DTC)

The Vector Control of Induction Motor [8,9] is an alternative to this type of control method. It has an immediate advantage in its performance as well as simplicity in design and construction. DTC [10] allows for 4 stator flux and torque control via the inverter state. Inverter state selection is still required in order to improve the motor's performance and achieve environmental compatibility, as well as perform optimally in the presence of disturbances.

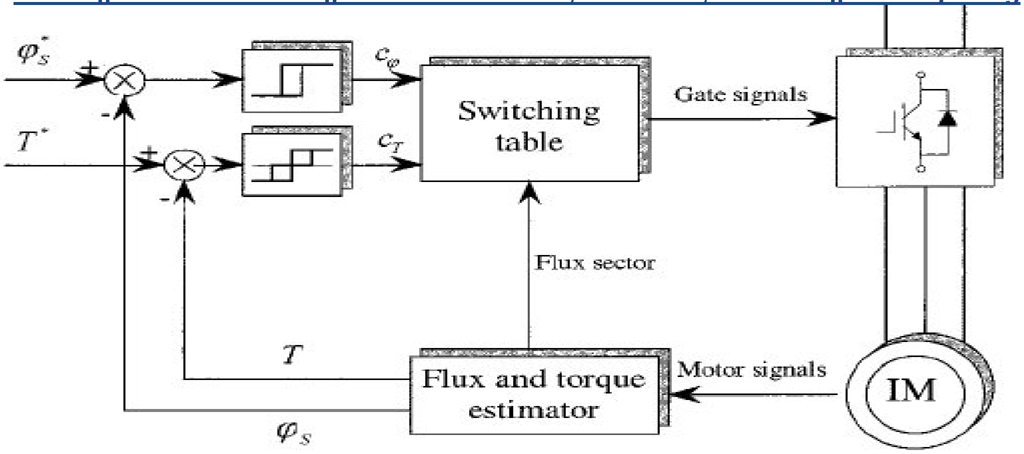

Figure 5 Diagram of a basic DTC control system.

In contrast to conventional DTC, which was applied to multiphase occasions in [11,42], five-phase DTC was employed in [43]. It is important to note that the number of voltage space vectors is 25 in a five-phase machine fed by two-level inverters, whereas 23 in three-phase counterparts. As a result of the redundancy of space vectors, inverter switching states are more precisely controlled and torque and flux are efficiently controlled, resulting in a quicker toque response and low ripple. As mentioned previously, this approach inevitably results in uncontrolled currents in the harmonic planes [43].

Field Oriented Control

Here, the FOC strategy in Figure 6 describes the torque-producing and the magnetizing components of the stator current separately to control both the motor speed and the torque.

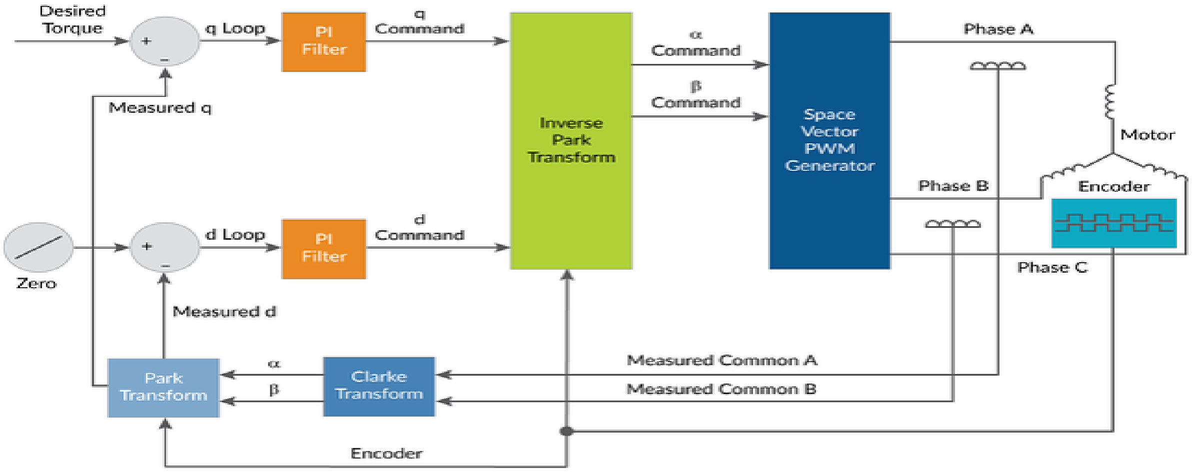

Figure 6 Diagram of Field Oriented Control

MULTIPHASE CONVERTERS TECHNOLOGY

A multiphase converter [20] is a variety of methods. As different power sources are used, VSCs and CSCs are separated into Voltage Source Converters (VSCs) and Current Source Converters (CSCs). In every converter discussed in this research, VSC is part of this category. A multiphase topology is classified as shown in Fig. 7 by how an AC-DC converter is created [49]. A matrix converter is a multiphase converter that includes both direct and indirect method. In contrast, open-winding and single-sided topologies are classified according to their neutral points. Without neutral points, two ends of open-wind topologies may be fed by one or two independent DC sources. Additionally, multi-sided topologies may have one or more neutral points.

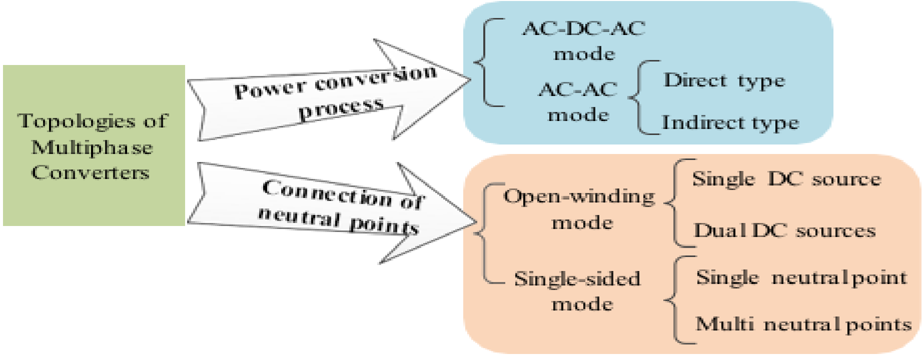

Figure 7 **Classification of multiphase converter topologies.**

AD-DC-AC mode

In this topology, multiphase AC power is produced by rectifying DC power and inverting it into multiphase AC power before feeding the multiphase machines. The DC bus decouples the AC input and output, which allows for the control of rectification and inversion.

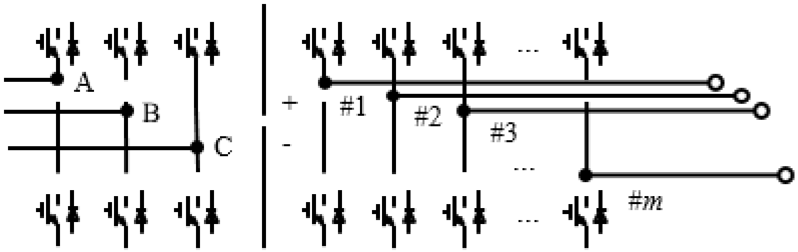

Figure 8 **The topology of AC-DC-AC multiphase converters.**

AC-AC mode

Matrix converters convert DC to AC power without passing through intermediate AC power links. Fig. 8 shows a direct matrix converter, which utilizes a single stage to perform voltage and current conversion (AC-AC). In contrast, the indirect matrix converter, shown in Fig. 8, requires two separate stages to perform voltage and current conversion (AC-DC-AC), but the virtual DC-link has no intermediate energy storage elements [6]. When phase number is high, the DC-link with energy storage is minimized, and the number of converters is reduced, switching devices become more numerous, and PWM modulation becomes more complicated [44].

CONCLUSIONS

This paper audits the drive and control procedures for multiphase machines. In view of the survey, it is seen that when the demand for high-power drive system increases, the number of phases and voltage levels would increase. It is seen that the number of SVs increases exponentially with the growth of phase number, the computation cost of DTC and MPC, which are based on the selection of space vectors, would be too high to be implemented in practice. In the fundamental and harmonic planes, CPWM concentrates on the current control in the fundamental and harmonic planes, resulting in an increase in the computation cost linearly with the phase number. Therefore, FOC would outweigh DTC and MPC in the future multiphase applications with large phase number. It is seen that the Direct Torque Control is more applicable for use where small and medium load consumption is required. The DTC is simple in design and has the ability to produce efficient torque control in transient and steady state operating conditions.

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